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## **Rocket Engine Oscillation Diagnostics**

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### **Abstract**

Rocket engine oscillating data can reveal many physical phenomena ranging from unsteady flow and acoustics to rotordynamics and structural dynamics. Because of this, engine diagnostics based on oscillation data should employ both signal analysis and physical modeling. This paper describes an approach to rocket engine oscillation diagnostics, types of problems encountered, and example problems solved. Determination of design guidelines and environments (or loads) from oscillating phenomena is required during initial stages of rocket engine design, while the additional tasks of health monitoring, incipient failure detection, and anomaly diagnostics occur during engine development and operation. Oscillations in rocket engines are typically related to flow driven acoustics, flow excited structures, or rotational forces. Additional sources of oscillatory energy are combustion and cavitation. Included in the example problems is a sampling of signal analysis tools employed in diagnostics. The rocket engine hardware includes combustion devices, valves, turbopumps, and ducts. Simple models of an oscillating fluid system or structure can be constructed to estimate pertinent dynamic parameters governing the unsteady behavior of engine systems or components. In the example problems it is shown that simple physical modeling when combined with signal analysis can be successfully employed to diagnose complex rocket engine oscillatory phenomena.

### **1. Introduction**

Rocket engine oscillating data encompasses many physical phenomena. Acoustic oscillations arise from flow-induced noise, cavitation noise, pressure transients, acoustic emission, flow/acoustic interaction, and rocket exhaust noise. Oscillations are also produced in unsteady flows by shearing, wakes, flow / structural interaction, and flow instabilities. Rocket engine oscillations can be characterized using analysis of data signals and modeling of physical behavior.

Measured rocket engine oscillatory data may be periodic or random and stationary or nonstationary. In general the diagnostic objective is to identify the type of dynamic system, determine the dynamic character, and replicate some aspect of the data using a dynamic model. Empirical modeling typically addresses driving mechanisms or resonance involving structures, acoustics, and flow.

The space shuttle main engine (SSME) is a high performance rocket engine intended for multiple re-flight. The SSME (Figure 1) includes liquid hydrogen and liquid oxygen pumping systems to convey these two propellants into the combustion chamber. These are cryogenic systems to provide the most compact storage. Preburners are used to power turbines that drive the pumps. Low-pressure pumps boost the pressure for efficient operation of the high-pressure pumps. The cool liquids are routed throughout pumps and nozzle to help protect materials exposed to intense heat and to warm the fluid before combustion. To control the acceleration experienced by passengers, the engines are throttled during ascent and the resulting thrust profile and tank depletion produces varying engine inlet pressures.



Figure 1. SSME static test firing

## 2. Problem Formulation

For the dynamicist, the diagnostics of rocket engine anomalies begins with signal analysis of the dynamic data. These signals may be periodic or random and stationary or nonstationary. In general the objective is to identify the type of dynamic system, determine the dynamic characteristics, and then analyze the response using a dynamic model (Figure 2).

Because of the variety of dynamic signals and potential mechanisms a long list of analysis methods have been used for rocket engine diagnostics. Time histories, probability density functions, and threshold methods are examples of time domain methods employed. power spectral density, cross-correlation, cross-spectra, hyper-coherence, phase synchronous enhancement,<sup>1</sup> maximum entropy method and further including topomap, isoplot (waterfall),

spectrogram, coherent phase wide band demodulation, and adaptive filters are examples of frequency domain methods employed. Mechanisms have been replicated using lumped parameter, empirical transit time, and single degree of freedom dynamic models or acoustic, wake oscillator, similarity, and method of characteristics models.

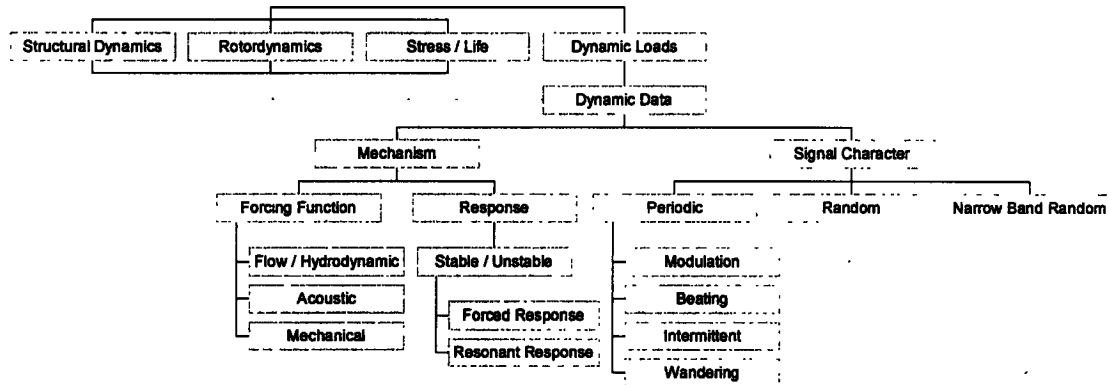


Figure 2. Dynamic data analysis

### 3. Approach

The approach to rocket engine oscillation diagnostics is to analyze measured acceleration, fluctuating pressure, strain, or force and combine that information with a model of pertinent dynamic mechanisms (Figure 3). In some cases the data and model have been used to determine statistical environments used for design loads or to diagnose the health of hardware. In other cases, the data and model are used after a failure to determine the failure mechanism or the sequence of events leading up to the failure.

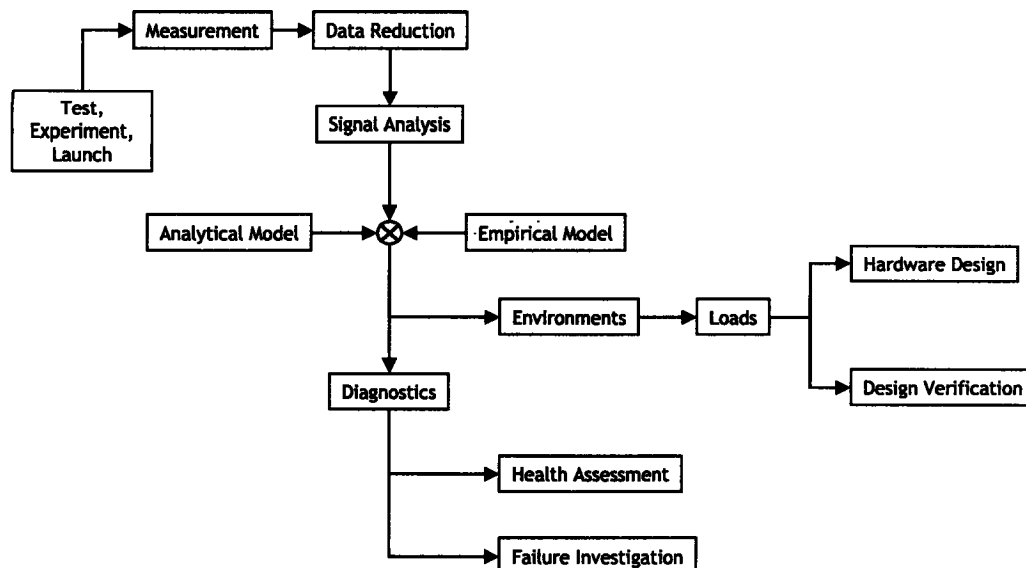


Figure 3. Oscillation diagnostics

As the rocket engine hardware ages there are an increasing number components that begin to reach the design life limits. The diagnostics of hardware issues relating to high cycle fatigue and life limits are performed to assess the potential for continued use of high time components. Furthermore, the measured oscillation environment history can be used to anchor dynamic response models to extend design life.

## 4. Applications

There are a multitude of dynamic phenomena that affect turbomachines in a deleterious manner. These phenomena include vibration response of stationary structures and rotating structures. The dynamic structural response is related to the excitation mechanisms such as rotordynamic (imbalance, misalignment, and rubbing) and flow oscillation phenomena (shear layer instabilities, flow/structural interaction, and acoustic resonance). For example, operational speeds near rotor critical frequencies often lead to excessive vibration and structural failure. A more subtle problem is flow cavitation which can cause vibrations, hardware pitting, and performance loss. Also, pump or turbine stall can affect the operational stability of the engine system; stator interactions with moving blades can provide strong forcing functions for structural elements. Rotordynamics, structural dynamics, and flow dynamics are important when evaluating the dynamic characteristics of rotating machinery.

Rotordynamics of turbomachines involve, primarily, the rotor modes. These modes are influence by the distribution of mass along the rotor, the location of supports, and the types of supports. In addition, various types of damping, bearing deadband, seal rubbing, and secondary forces must be analyzed to properly evaluate rotor response. In general, vibration diagnostics can be used to identify the classic rotating machinery problems. Structural dynamics of turbomachines encompasses the evaluation of stationary structures such as ducts, struts, vanes, tubes, and housings; and rotating structures such as impellers, inducers, turbine blades, and turbine disks. Determination of forced and resonant response to various excitation loads is required to evaluate component life or to evaluate structural failures if they occur.

Rocket engine internal flow passages, hot gas drive systems, and propellant feed systems are sometimes designed (for structural purposes) with bluff bodies in the flow. In addition, there are flexibility in ducts, liners, and tubes that may be excited by flow. Analysis of flow induced instabilities in turbomachines and related systems must be accomplished to appropriately identify high frequency signals. Flow dynamics in turbomachines can be subdivided into the turbulent flow loading, discrete flow loading, flow/structural interaction, and acoustic resonance loads. The flow related phenomena are characterized by dimensionless frequency (equation 1) in terms of performance parameters. Resonant acoustic cavities<sup>5</sup> are often considered as contributing to or enhancing destructive vibration phenomena. Typically, anomalous discrete high frequency vibrations that are not synchronous related are investigated for possible acoustic cavity origins.

$$\underline{f} = \frac{f \cdot D}{U} \quad (1)$$

The flow field leaving a vane row has a periodicity, in space, corresponding to the number of vanes. Similarly, the flow field at a rotor inlet has periodicity, in time and space, corresponding to the rotational speed,  $N$ , and the number of blades. The interaction of these two complex flow fields can be analyzed using the components of the Fourier series of the stator and rotor. This is a modulation process of the rotating periodicity and the stationary periodicity. Wakes from upstream structures can interact with downstream structures. If one of the structures is rotating the result is complex nonstationary flow phenomena. These phenomena can occur in pumps (impeller / diffuser interaction) and turbines (rotor / stator interaction) with consequences of high vibrations and noise. The coincidence of pressure pulsation with structural modes can lead to structural damage.

#### 4.1 Example, Lox pump inducer water flow test

Design guidelines and environments for a Lox pump were determined through an inducer water flow test.<sup>2</sup> The new SSME HPOTP design was water flow tested to verify suction performance and characterize dynamic loads. The test article was instrumented for oscillation environments and high frequency signal analysis was used to determine performance, steady & dynamic loads,<sup>3</sup> and identify unsteady flow phenomena. The results were described by directly plotting dynamic data versus pump parameters such as the cavitation coefficient (equation 2). The cavitation coefficient,  $\tau$ , was determined from the net positive suction head, NPSH, and the tip speed,  $U$ . The intensity of cavitation was determined from the coherent phase of cavitation modulated by unsteady flow.<sup>4</sup>

$$\tau = \frac{NPSH \cdot 2g}{U^2} \quad (2)$$

The unsteady characteristics of the inducer were detailed in terms of fluctuating pressures, blade strain (with the instrumented inducers), and accelerations. The suction ramps were repeated with the various inducer designs. Fluctuating pressure was measured at the pump inlet flange, volute outer wall at the inducer tip, inducer outer wall at blade  $\frac{3}{4}$  chord, and outer wall at inducer discharge. The inducer clearance and leading edge angle were varied over the course of testing to reduce the cavitation dynamics.

The high frequency data were analyzed and correlated to the operating parameters and to visual observations of the flow (Figure 4). The cavitation characteristics observed on these tests followed a repeatable sequence. Initially, at relatively high inlet pressure, small cavitation clouds are present behind each of the four inducer blades. The inducer responds with high level 4N vibrations during this type of cavitation. The second type of cavitation occurred when the inlet pressure was lowered until two symmetric cavitation clouds appeared behind alternate blades. The inducer responded with high level 2N vibration during this type of cavitation. A third type of cavitation occurred just before head fall-off with two alternate blade cavitation clouds of different size. The inducer housing responded with high 1N vibration during this type of cavitation.

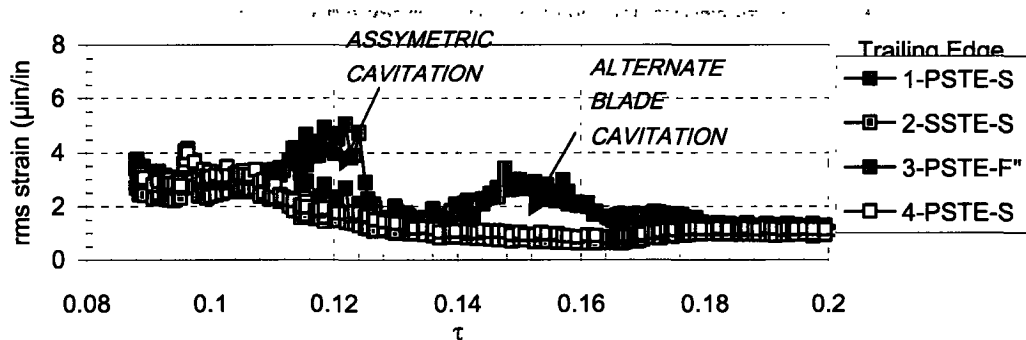


Figure 4. On-blade trailing edge micro-strain

## 4.2 Example, fuel pump anomalous frequency

The SSME low pressure fuel pump (LPFP) has exhibited an anomalous frequency at around 330 Hz. The anomalous frequency was detected on the low pressure fuel pump and high pressure fuel pump accelerometers and signal analysis of these measurements provided the data for diagnostics. Aspects of the anomaly are modulation and switching. Modulation frequencies commonly accompany the 330 Hz frequency and show up as side bands of sync harmonics. The occurrence of the 330 Hz frequency seems to switch with the occurrence of a high 2N (Figure 5).

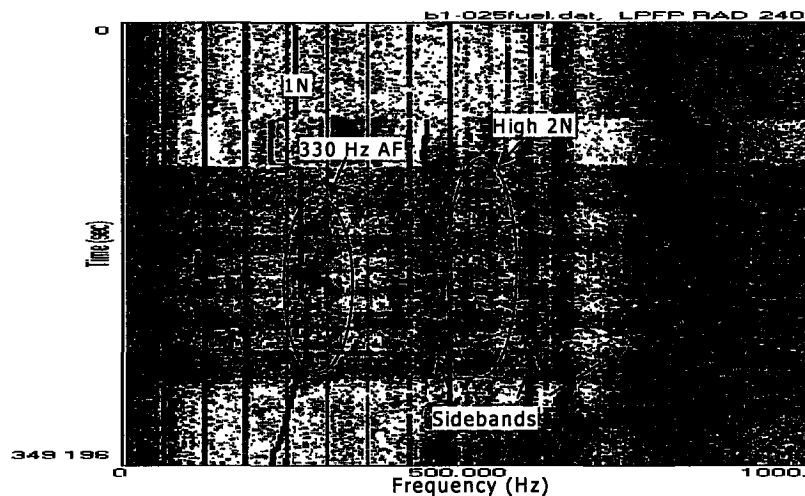


Figure 5. LPFP accelerometer spectrogram

A unique set of data became available that helped reveal some of the characteristics of the 330 Hz anomalous frequency. On a test with an uncontrolled cycling tank pressurization system, variations in suction pressure clearly showed an alternating intermittency of 330 Hz and a high 2N. Because the fuel pressure resulted in varying engine fuel inlet pressure it was possible to determine the trend of nondimensional frequency versus cavitation coefficient,  $\tau$ . The 330 Hz frequency was nondimensionalized using the tip velocity,  $U$ , and tip diameter,  $D$ . This simple model (Figure 6) identified the 330 Hz as a cavitation phenomenon occurring at low suction

pressure. Furthermore, the suction characteristics of the data suggested that alternate blade cavitation was the source of the high 2N.

$$f_{330} = \frac{U}{D} \cdot (3.857 \cdot \tau + .2744) \quad (3)$$

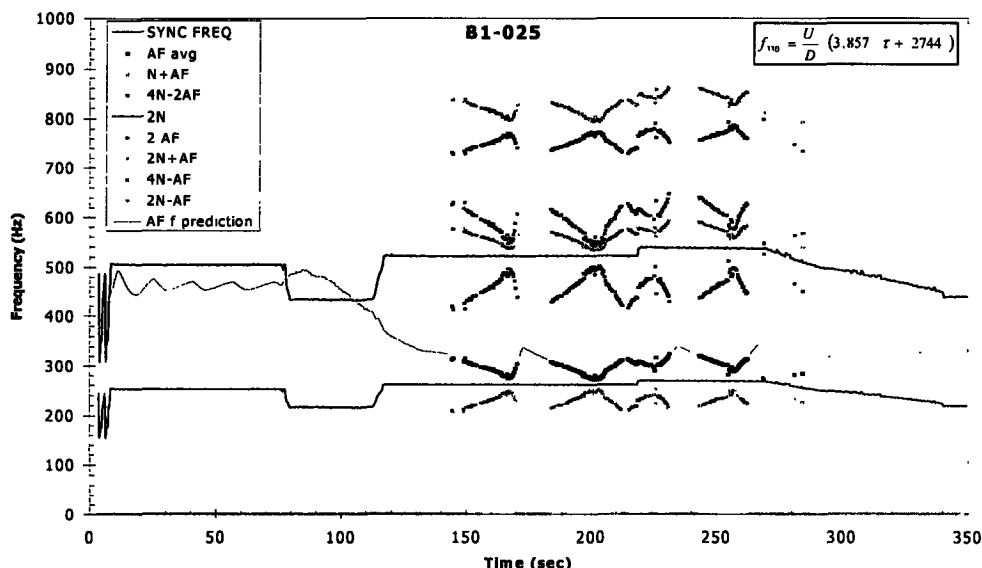


Figure 6. 330 Hz anomalous frequency prediction

### 4.3 Example, turbine nozzle vane cracks

A low pressure oxidizer turbopump unit was recently being refurbished when a cracks were found on the turbine nozzle vanes. Because this was a "low time" unit a team was formed to investigate the vane cracking mechanism. Several possible dynamic vane cracking mechanisms were considered: Stator / rotor interaction, wake excitation, and structural modes of vibration. Based on these analyses the most plausible mechanism was vane 1<sup>st</sup> bending driven by oscillating lift from vortex shedding at the trailing edge.

High frequency data was searched for evidence of this phenomenon with several limitations. The only available measurements were accelerometers on the outer case. These accelerometer typically had a resonance in the range of the postulated mechanism. The data acquisition and recording systems were not intended for such high frequencies resulting in an attenuation of 45.6 dB at 34 KHz. It was concluded that there was a possible amplification due to accelerometer resonance countered by attenuation due to acquisition and recording.

A look at the accelerometer data from an early test of a cracked unit revealed a significant discrete oscillation at 34 KHz when operating below 100% power level. The frequency and amplitude show the distinct characteristics of a flow / structural "lock-in" (Figure 7). The 34KHz oscillations were several orders of magnitude above the spectral noise floor.

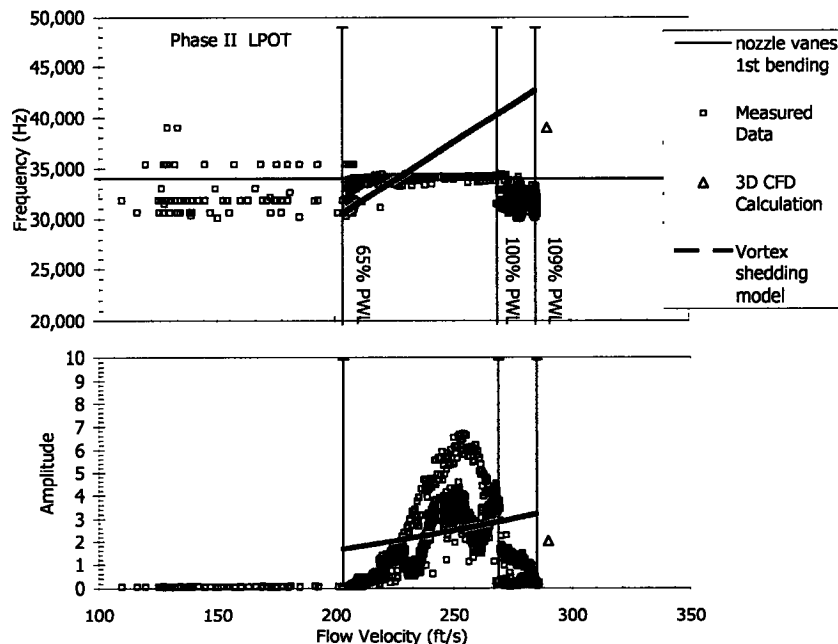


Figure 7. Frequency and amplitude versus flow

Though there are unknowns such as the transmissibility from vane to accelerometer and amplification by accelerometer resonance, it seems likely that the vane is being excited by the flow. Based on these results the flow loading was used to evaluate LPOT vane life.

## 5. Conclusion

It has been discussed and shown that rocket engine oscillating data encompasses many physical phenomena. Examples of rocket engine oscillations and the respective data signals have been discussed. Finally, modeling of physical behavior has been shown to aid in diagnostics.

## References

1. Jong, J.Y., Dorland, W., Fiorucci, T., Zoladz, T., and Nesman, T., "Coherent Phase Line Enhancer for Rotating Machinery Diagnostics," AIAA 37th Joint Propulsion Conference, Salt Lake City, Utah, July 8-11, 2001
2. Bordelon, W. J., Gaddis, S.W., and Nesman, T.E., "Experimental Investigation of the Cavitation Modes of a Four Bladed Inducer," 2nd Joint ASME/JSME Fluids Engineering Conference, August 13-18, 1995
3. Herda, D.A., and Gross, R.S., "High Pressure Oxidizer Turbopump Inducer Dynamic Design Environment," NASA Technical Paper 3589, November 1995
4. Jong, J., Nesman, T., Bordelon, W., Jones, J., and Zoladz, T., "Coherent Phase Wide Band Demodulation Technique for Turbomachinery Cavitation Detection and Monitoring," Joint Conference on Integrated Monitoring, Diagnostics and Failure Prevention, April 22-26, 1996
5. Lucas, M., Noreen, R., Sutherland, L., Cole III, J., and Junger, M., "Handbook of the Acoustic Characteristics of Turbomachinery Cavities," ASME Press, New York, 1997